TECHNOLOGY TRADE SPACE DEVELOPMENT IN CREW-SYSTEMS FOR LONG-RANGE STRIKE

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One promise of constructive simulation is in providing an exploratory environment within which one can identify factors critical to performance – effectiveness tradeoffs. We will discuss construction of such a trade space by focusing on the methodology guiding the Crew-systems for Long-range Strike (CSLRS) program. The methodology uses an iterative, spiral process to define the trade space, develop system and operator descriptions, parameterize the trade space and analyze performance against requirements. We use the approach advocated by Rasmussen (1983; 1985) to characterize the trade space and system requirements, combined with a constructive simulation approach to describe specific technologies and human operators, and to analyze performance against requirements. Four vectors through the trade space have been identified to date: Image fusion, synthetic/enhanced displays, dynamic mission re-planning and human-system integration performance measures. We currently are using the Rasmussen abstraction hierarchy, in conjunction with standard subject matter expert interviews, to guide our definition of specific issues surrounding these vectors. As we identify specific technology challenges, models are developed within the CART environment. The technology challenges are then explored against representative scenarios. The new challenge in this particular effort is to understand mission effectiveness in a 2025 timeframe and to use this understanding to develop a technology maturation roadmap for the four trade space vectors identified above. Constructive simulations serve a critical enabling function in this process by allowing rapid development and testing of alternative technologies within the context of the specific trade space of interest. As part of our presentation we will discuss unique methodological requirements arising out of modeling and simulation activities targeted at future technologies and scenarios.

Introduction

Evaluating technology effects on advanced aircraft systems effectiveness is a challenging problem, made more so when system effectiveness is moderated by human performance considerations. A promising way to address this challenge is through constructive simulations. These can provide exploratory environments that allow analysts to identify factors critical to performance – effectiveness tradeoffs. Merely constructing simulations, however, does not solve the technology evaluation problem. Constructive simulation, by its nature, allows great flexibility in technology combination, level of analysis and dimensions of evaluation. These factors combine to create a trade space that can be unmanageably large. A primary goal of our methodology is to bound the trade-space in a principled manner. Doing so allows technology evaluations that are focused on the most relevant aspects of a technology investment program. Our method is based on the Technology Identification, Evaluation and Selection (TIES) methodology for aircraft design articulated by Mavris and Kirby (1999). TIES enables technology trade-offs in the early stages of aircraft design by relying on accepted engineering models of, for example, propulsion, materials and aeronautics. Reliance on such models allows an engineering design team to conduct the physical modeling and design of experiment activities required to assess the role of technologies on predicted aircraft performance through their effects on structures, wing sizes and loadings, and propulsion as well as on well-behaved physical parameters like lift and drag. While the TIES methodology seems well-suited to technology prediction in traditional engineering domains, it exhibits shortcomings when applied to crew-system integration applications. First, few engineering models exist for human performance that lend themselves to predictions of technology effects. There are several human cognitive performance architectures currently used to model behavior in domains similar to military aircraft operations. These include ACT-R (Anderson and Lebiere, 1998), SOAR (Rosenbloom, 2000), SAMPLE (Zacharias, 2000) among others. However, some of these architectures rely on human performance data that is somewhat controversial or require modeling at such a low level that their use for early-stage technology evaluations is limited. Others manage these problems by either "turning off" behavioral functions or limiting their levels of analysis to broad behavioral aggregates that makes informative technology evaluation difficult. Second, critical portions of the TIES methodology rely on expert judgment. For example, development of a technology impact matrix (to be discussed in detail later) is based on consultation with subject matter experts in sub-disciplines of aircraft configuration as well as in the technologies under evaluation. These experts rely on both their own analysis and on disciplinary models and historical data in making predictions of performance changes correlated with each technology. Because these models are deterministic the predictions are more reliable than would be the case if the models were stochastic, as is the case in the human behavior representation community.

Furthermore, few of the parameters used in accounting for human performance are sufficiently well-behaved to support performance predictions in the presence of new technologies. This weakens the TIES methodology as

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presented by Mavris and Kirby by preventing use of both accepted models and the design of experiments method. Simply put, the problem space for human performance is intractably large for a traditional TIES approach.

We attempted to address these shortcomings by integrating the TIES methodology with CART's task network and human performance modeling capabilities. Our methodology relies on a series of principled analytical steps to define a subset of the possible trade space that represents the most informative technology evaluation possible. Each step in the methodology is designed to constrain one dimension of the trade space. Once identified, these are then combined into an evaluation environment and represented within CART. Technology alternatives are then compared against a baseline and each other to assess overall impact on crew-system effectiveness.

Our methodology is shown in Figure 1. In this section we briefly describe the methodology at a high level. Subsequent sections will discuss each step in greater detail.

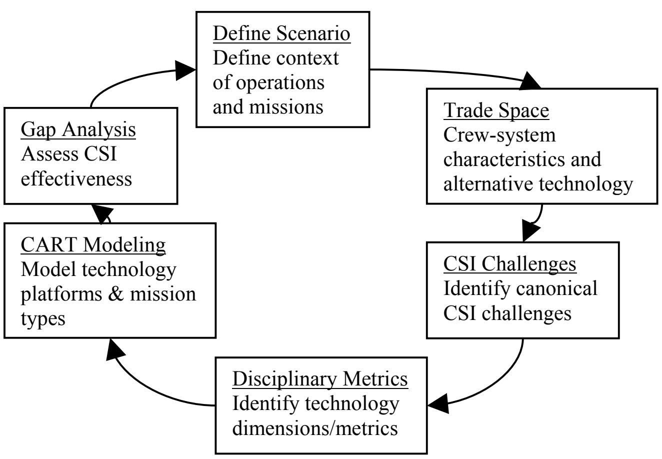

Figure 1. Methodology Overview

We begin with development of a general scenario and a set of excursions capturing plausible operational variations. The scenario provides a structure within which the technology evaluation is situated. The absence of a scenario would weaken the validity of predictions regarding the performance of the crew. The need to situate our evaluations of new technologies leads to step 2, development of platform alternatives. This is one way in which our methodology differs from that of Mavris and Kirby (1999). Our technology evaluations required developing alternative platform concepts because of significant interactions between the platform and specific missions. For example, platform concepts involving (1) a low-altitude, subsonic aircraft versus (2) a high-altitude hypersonic aircraft are likely to perform very differently across several types of long-range strike missions. All of these interactions must be considered in an overall evaluation. Our next step is to develop a morphological matrix. This provides a structured method of identifying technology combinations from among many potentially useful candidates (Twiss, 1992). The universe of possible technologies is constrained by including only those that relate to the fundamental characteristics of the system under evaluation. Since the fundamental characteristics of a propulsion system differ from those of a crew-system technology alternatives appearing in respective morphological matrices also will differ. When candidate technology alternatives have been identified, they are aggregated into a set of platform alternatives. These are combined with the mission excursions into a CSI challenge matrix. Challenges specific to platform-excursion combinations are then identified. Summary challenges across this space are then identified using a set of rules to be discussed below. Technology dimensions and disciplinary metrics are identified for each of the CSI challenges in the next step. This information is combined with the platform alternatives. CART models are then developed to support evaluations of platform effects on mission performance. The final step is to conduct gap analyses comparing each platform to baseline technology and to each other. The remainder of the paper discusses each step of the methodology in detail.

Methodology Application and Results

Scenario/Excursion Construction. Our method begins with construction of a base scenario and excursions from this base. Scenario construction serves as the fundamental problem definition activity within which technology evaluation is situated. This establishes the context and boundaries of subsequent performance and technology evaluations. Our scenario was constructed by envisioning a standard geo-political background leading to a plausible military confrontation. The background context was populated with technologies that an adversary can be expected to possess within a timeframe approximately 15 years in the future. This information was obtained through open sources. These technologies were "placed" within the scenario to present challenges to the platforms that would be evaluated as part of our technology selection. We then developed a baseline mission and associated flight profile. Excursions then were defined to investigate performance under several standard mission variations within current Air Force doctrine. Five excursions were included: Harbor mining, runway suppression, threat suppression, time-critical targeting and attack of a hardened tunnel containing intermediate range missiles.

Morphological Matrix for Technology Concept Identification. Mavris and Kirby (1999) define a morphological matrix as a structured means of decomposing a system into combinations of conceptual subsystems that will satisfy mission requirements. For this decomposition to be productive, it is necessary to identify a critical set of characteristics that will be addressed by the technology combinations. In our case this set is encompassed by the crew and crew-system. We identified 6 characteristics of a long-range strike crew system: flight control, command and

control, situation awareness, location/orientation, safety and lethality. We then combined these with alternative performance attributes into a morphological matrix. The matrix is shown in Figure 2. Cells of the matrix were populated with alternative attributes of each characteristic. For example, flight control alternatives include automatic control, manual control and hybrid means of control. Combining attributes from the resulting table yields individual concepts for further study. Although it is possible to generate a large number of concepts from the morphological matrix the number of plausible concepts typically will be smaller than the factorial combination of all tabled attributes. Three platform alternatives were chosen for this evaluation: arsenal platform, low supersonic and high supersonic. These alternatives represent a wide range of capabilities both with respect to fundamental dimensions of an airframe: Altitude, airspeed, weapon mix and capacity, threat management strategies, communication capabilities, and with respect to the crew-system characteristics shown on the left of matrix.

LRS crew system characteristics	**1**	**2**	**3**
Flight control	Automatic	Manual	Hybrid
Command & control	Static	Dynamic	
Situation awareness	Perceptual fusion	Contextual comprehension	Prediction
Safety against threats	Fast	Highly lethal Self-defense	Stand-off
Target lethality	Weapon volume	High weapon accuracy	Weapon variety
Detectability	Stealthy	Small	Spoofing
Mission flexibility	Totally pre-planned	Totally adaptive	Hybrid

Figure 2. Morphological Matrix

Identify Crew-system Integration (CSI) Challenges. Construction of a morphological matrix allows analysts to define a concept space. However, further progress will not be possible unless specific CSI challenges are identified. It is these CSI challenges that the technologies are evaluated against. Accordingly, the next step involved construction of a platform by mission excursion table populated with CSI challenges. Figure 3 provides a partial example of such a table. The content of this table is developed by means of an analytical process involving experts in mission requirements, platform characteristics and crew-system integration. The process was guided by consideration of the LRS crew-system characteristics identified during morphological matrix definition. For example, an arsenal platform executing a runway suppression mission exhibits specific challenges in the areas of situational awareness, safety against threats and target lethality. These were placed into the appropriate cells of the table shown in Figure 3. It should be noted at this point that not all cells in a CSI challenge matrix will necessarily be completed. It is possible, in fact probable, that some platform concepts will be inappropriate for particular missions. Thus, the arsenal platform is unlikely to be appropriate for a harbor mining mission.

Note that Figure 3 also contains marginal cells representing summary information across both mission types and platforms. Summarizing across missions and across platforms allowed us to identify manageable subsets of CSI challenges affecting multiple platforms and missions. Further summarizing across the marginals produced a canonical set of challenges that supported the task network modeling to be discussed below. Creation of the summary platform/mission challenges or the canonical challenge set is not simply a matter of enumerating the contents of cells in the table. Rather, we discovered several rules that were useful in guiding the process. First, challenges that appear consistently across cells should be captured. Second, technology availability should be considered. CSI challenges that seem to be satisfied by currently available (old) technology should be eliminated from further consideration. Third, mission phase criticality affected the "weighting" of some CSI challenges. Since some mission phases are arguably more important than others (e.g., threat management over cruise) the challenges associated with the former phases should be preferred in the summarization process. Fourth, challenges that are related to brittle technologies should appear in summaries. An example of a brittle technology would be that of communication. Although current communication capabilities are impressive, they also can be easily disrupted. Disruption would lead to potential mission degradations that should be explored with new technology concepts. Fifth, the perceived cost of new technologies should be considered. While it is possible, for example, to imagine particle beam weapons as potential solutions to some challenges the cost of such technologies is unlikely to make them viable within the time frame under consideration. It probably would not be productive to include CSI challenges related to these technologies in subsequent analysis. Sixth, challenges that might be associated with technologies having particularly high payoff were added to the summaries. Based on the mission execution challenges identified in Figure 3, in conjunction with the summarization rules discussed above, four crew-system integration (CSI) areas were identified as critical to mission success. These were image fusion, synthetic/enhanced vision, dynamic mission re-planning and human-system technology integration.

System Effectiveness Metric Identification. Development of the morphological matrix results in identification of aggregate technology concepts. The CSI challenge matrix helps identify CSI areas critical to mission success. Our next step was to relate this technology information to human

Mission Excursion	Arsenal	Low supersonic	High supersonic	**Mission Challenge Summary**
Harbor mining	N/A	• Pop-up threat detection • Mine placement to planned coordinates	N/A	• Weapon delivery accuracy • Threat management
Runway suppression	• Weapon guidance • BDA • Coordinate updates	• Effective target coordinate updates • Effective SAR imaging	• Weapon delivery to precise coordinates from mach 10	• Weapon guidance • Effective BDA • Multiple image sources • Mission updating
SEAD	• Weapon guidance over the horizon must be highly accurate • Multiple targets with coordinated attack management	• Protect against passive detection • Effectively merge SAR, EO, tactical and human visual information	• Target coordinate updates will be crucial • Target imagery	• Target location updates • Multiple image sources • Weapon guidance and control
Mobile TCT	N/A	• Maintain SA in real-time environment • Effective integration with all ISR assets	• Target updates must be timely	• ISR integration
Hardened tunnels	• Weapon guidance over the horizon must be highly accurate • BDA	• Must have accurate target coordinates at point of release • BDA	• Weapon guidance on-board?	• Target coordinate accuracies • BDA
Platform Challenge Summary	• Over the horizon BDA • Long range weapon guidance • Target/coordinate updates	• Pop-up threats • Imaging effectiveness • ISR integration	• High speed weapon delivery • Mission update timeliness	• Dynamic re-planning • Image fusion • Synthetic/enhanced vision • Human-system integration

Figure 3. CSI Challenges

performance by constructing a technology impact matrix (Mavris and Kirby, 1999), an example of which is shown in Figure 4. This was done in a 2-step process. First, technology dimensions of each CSI challenge were identified. This process relied primarily on expert judgments and literature review. For example, the critical dimensions of dynamic mission re-planning include network architecture, uplink/downlink method, data throughput rate, data structure, and data sources. Second, disciplinary metrics were identified for each technology dimension. These metrics are referred to as k-factors by Mavris and Kirby and represent the critical addition at this point in evaluation. Figure 4 displays the technology impact matrix for dynamic mission re-planning. Three disciplinary metrics are shown for the technology dimension of uplink/downlink method: (1) time needed to input new information into on-board automated systems (update time), (2) time input accuracy during mission updating, and (3) the ratio of manual to automated updating required (update efficiency). In general, as well as for the evaluations discussed here, sources of the k-factor vector for areas under evaluation include interviews with subject-matter experts, literature reviews, the expertise of analysts involved in the evaluations and so on. Note that the combination of technology dimensions of the CSI challenges and technology concepts aggregated into platforms constrains the technologies available for consideration during this phase of overall evaluation. Maintaining this constraint is important in preventing a run-away consideration of all possible technologies, though one can always go back to the morphological matrix to formulate new concepts if desired. Two other factors help to maintain this constraint: (1) consideration of technologies rather than specific applications of technologies and (2) keeping the evaluations situated strictly within the scenario excursions defined in the first phase.

	Technologies		
Disciplinary Parameter Vector (k-factors)	Arsenal	Low Super-sonic	High Super-sonic
Situation awareness			
Workload			
Memory load			
Attentional efficiency			
Stress			
G-loading			
Goal priority			
Perceived goal cost			
Message comprehensibi			
Message perceivability			

Figure 4. Technology Impact Matrix

CART Modeling. Figure 4 sets the stage for the technology evaluations. However, in many instances, including those discussed by Mavris and Kirby (1999), these evaluations rely on either well-documented engineering models or on the predictions of experts in the effects of the technologies being evaluated. In the case of human-systems integration, however, predictions based on these sources either are unavailable or of suspect reliability. The CART environment, as described by Martin, Brett and Hoagland (1999) provides a way to empirically conduct the evaluations needed to make technology investment recommendations.

The CART environment is a goal-oriented, task network modeling tool based on the IMPRINT discrete event simulator. It allows analysts to develop hierarchical task networks describing the structure of mission execution to an arbitrary level of detail. The task network approach provided by IMPRINT, combined with an ability to integrate tasks with goal descriptions, allows one to evaluate a range of technologies by describing their effects on operator performance at whatever level of analysis is desired. Within the context of the CART environment technology effects are apparent in two ways.

First, by affecting task network structure a particular technology can affect mission outcomes by adding, deleting or changing the ordering of network elements. For example, a mission updating technology that automatically inputs target coordinates into a flight computer might result in the elimination of several tasks on the part of an aircrew. The resulting effect on a running CART model might be an increase in target coordinate recording accuracy, a decrease in time required to register new coordinates with the flight computer, an increase in the number of targets that can be entered into the flight computer per unit time and so on. At the same time, automating mission updates might require an addition of new tasks that might also affect accuracy, time and efficiency. These tradeoffs, and the resulting effects on mission effectiveness, are explored by modeling the task network associated with the technology in CART.

Second, a technology can affect the performance values associated with task execution. This can happen when a technology influences the accuracy with which a task can be carried out or the reliability with which the task is performed. An example of an accuracy effect was found with technologies requiring manual re-programming of target coordinates. As the number of coordinates requiring updating increased, the accuracy of updates decreased due to working memory load. An example of how technology affects task execution reliability was observed with technologies that relied on satellites for communication of mission updates. When communication mediated by these satellites was disrupted, other methods were used. However, task execution performance became much more variable with the result that overall mission performance degraded across multiple mission simulations. CART allows an analyst to vary these two parameters by (1) defining mean accuracy associated with a particular task and (2) specifying the distribution and variance associated with a task.

Figure 4 summarizes the manner in which model-based evaluations were conducted for dynamic mission re-planning. A disciplinary metric vector was defined for each of the technology dimensions identified in earlier phases. A subset of the dimensions is shown in the Technology Impact Matrix. For example, metrics for the uplink/downlink method included the time required to complete updates, the input accuracy associated with information entry, and update efficiency: A measure of how many updates could be successfully executed per unit time. CART models were developed for each of the three platforms representing technologies to be evaluated. Model runs then were conducted. The resulting effects on each of the disciplinary metrics would be shown in Figure 4 as either positive or negative percentage changes in each metric, relative to performance in a baseline system. This information would then support the gap analysis discussed below.

Comparative Gap Analysis. The final step of our methodology is to assess the mission effectiveness associated with the technologies comprising our 3 evaluation platforms. To do this we develop a model of each system metric based on the vector elements of Figure 5. In most cases we anticipate that these models will take the following form:

$$R = b_0 + \sum b_i k_i + \sum b_{ii} k_i^2 + \sum\sum b_{ij} k_i k_j$$

In this form R represents a system metric, b_i represents linear regression coefficients, b_{ii} represents quadratic coefficients, b_{ij} represent cross-product coefficients and each k term represents k-factors from the parameter vector in Figure 4.

Discussion

The methodology discussed above provides a principled way of moving from an open-ended space of potential technology concepts to predictions of technology effects on human-system effectiveness. The value of this method resides in providing: (1) a way to define a bounded trade-space within which technology alternatives can be identified, (2) a method of combining mission requirements with high-level trade-space technology alternatives to assist in identifying areas to help focus technology predictions, (3) a modeling tool to represent the task networks required to carry out mission requirements using identified technology concepts and (4) an analysis method relating technologies directly to crew-system effectiveness metrics. Future work will be concentrated in several areas. The first addresses how to represent the technology under review. If representing technology can properly be considered a hierarchy, then the question becomes what level of analysis is meaningful. Our technology representations to date have primarily been functional and have occupied a fairly high level of aggregation. However, it is possible to represent technology on at least two lower levels: Technology class level and a specific system level. These levels, when applied to radar for example, might include sensing, SAR and a specific system or application. Choosing one representational level or another when executing the methodology outlined here would lead to different simulation outcomes.

A similar question arises in consideration of human performance. Again, our simulations to date have been limited to relatively high levels of analysis in our human performance modeling. While maintaining this level has been useful in comparing platform configurations and in identifying broad crew-system effectiveness issues, it is less useful in evaluating specific alternatives (e.g., SAR versus EO as a target recognition aid). On the other hand, moving the human performance level of analysis to a low level risks (1) creating a problem of proliferating process boxes and (2) disconnecting human performance evaluations from an overall understanding of system effectiveness. Worse still, the levels of analysis problems for technology and human performance are interrelated.

A third challenge for future work with this methodology is how to account for variation in crew performance, at both the task and method levels. Crews often achieve goals by combining tasks in different sequences or by using different tasks altogether. Additionally, tasks can be accomplished through variations in methods. This variability creates problems for technology evaluation, as it is difficult to state with certainty that one combination of technology is clearly superior to another without regard to task and method variation.

Finally, the problem of technology interactions must be addressed. As has been pointed out by Overdorf (2002), technologies might lead to performance improvements when considered in isolation but to performance degradations when combined. This raises the problem of combinatorial explosion in which all possible combinations of all technology candidates must be considered. We finessed this problem in the current study by combining technologies into functionally defined platforms defined to address only the mission excursions of our scenario. However, this strategy is more ad hoc than we would like.

We feel that the methodology discussed here, particularly the addition of the CART modeling and simulation environment, holds great promise for evaluating technology effects on crew-system performance. As the challenges outlined above are addressed, the general method should greatly facilitate technology investment decisions and the place of crew-systems in simulation-based acquisition.

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